Light Water and High Temperature Reactor Opportunities: Flexible, Low Carbon Energy Generation for Thermal and Electric Applications

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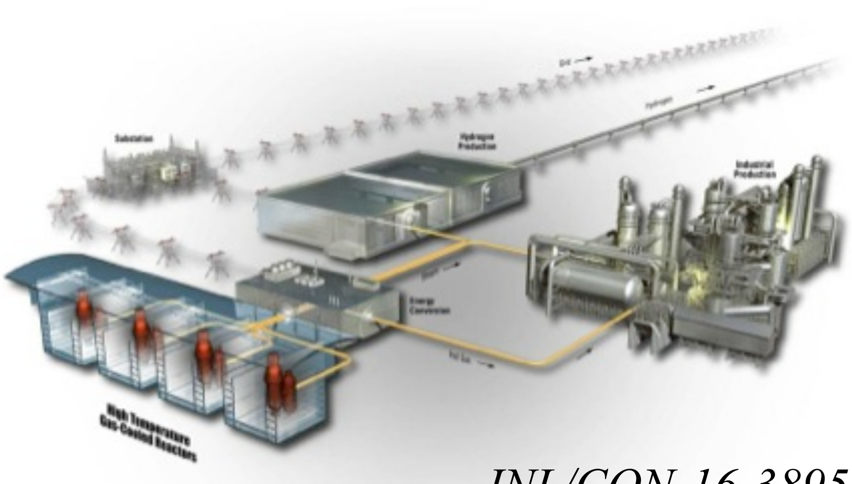


June 9, 2016

INL/CON-16-38950

Idaho National Laboratory

Goals / Opportunities

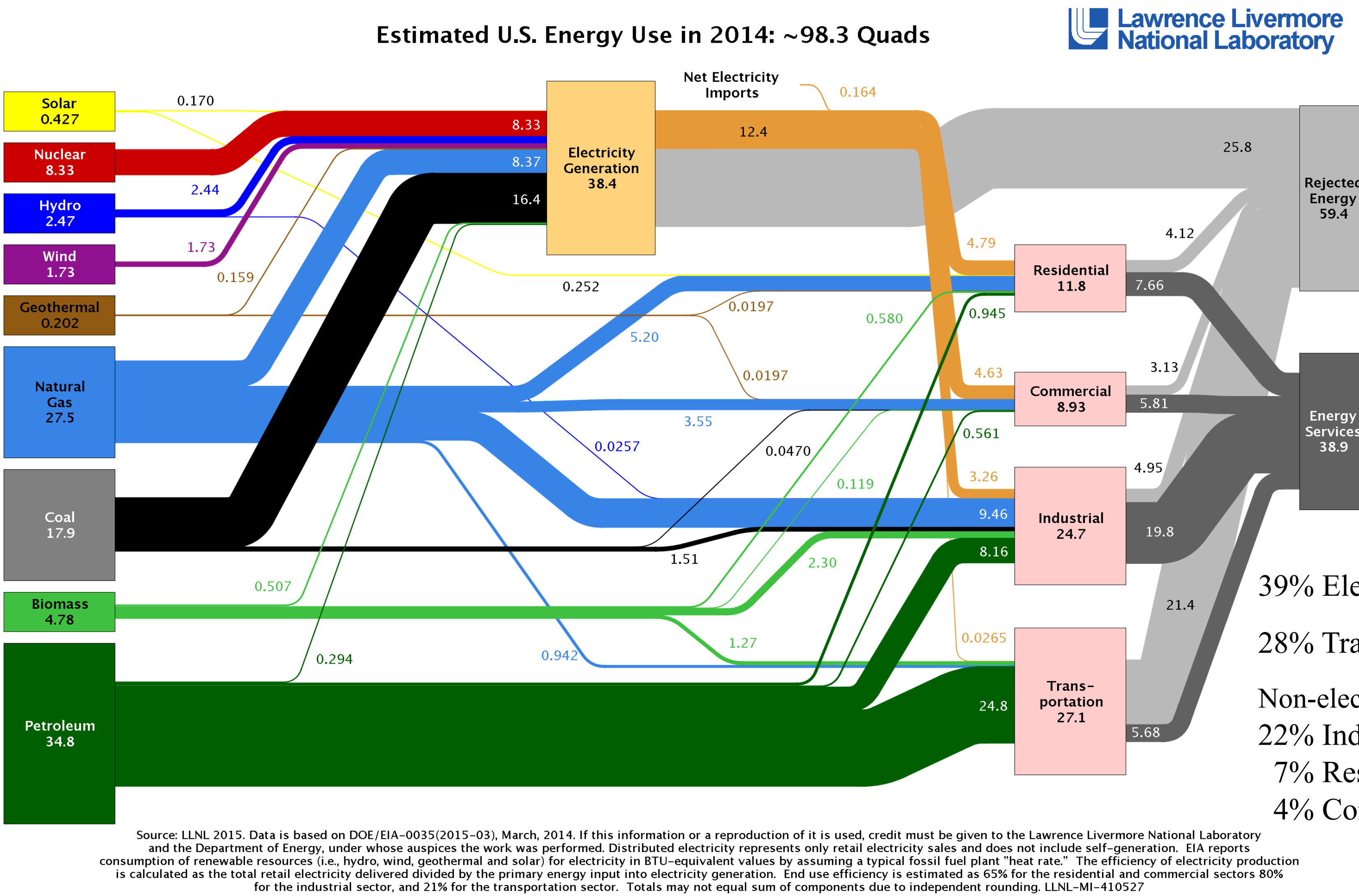
- *Develop **flexible energy systems** that exhibit **reduced emissions** for electricity generation using high efficiency power cycles.*
- *Expanded use of **low-carbon energy** for industry and transportation.*
- ***Enhanced grid operation and generator profitability** through production of non-electric commodities and participation in the reserve capacity market.*

New Operational Paradigm:

- Integrated industrial-scale energy systems with internally managed resources
- Dispatchable electricity to meet grid demand with less energy storage
- Thermal energy input to industrial applications (minimize cycling of base load generators)

→ System operation in dynamic fashion.

Estimated U.S. Energy Use (2014)



39% Electricity (total)

28% Transportation

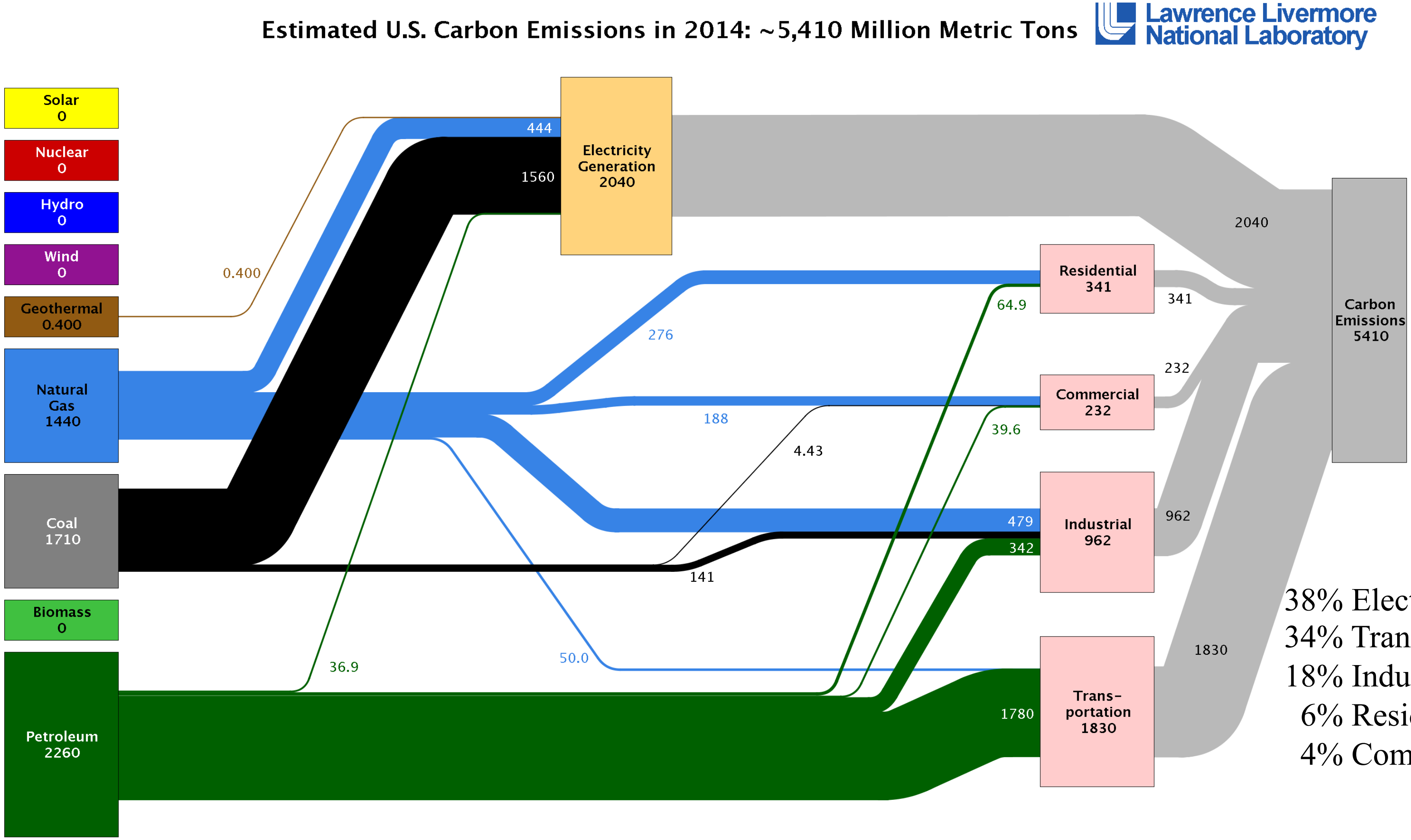
Non-electric energy use:

22% Industrial

7% Residential

4% Commercial

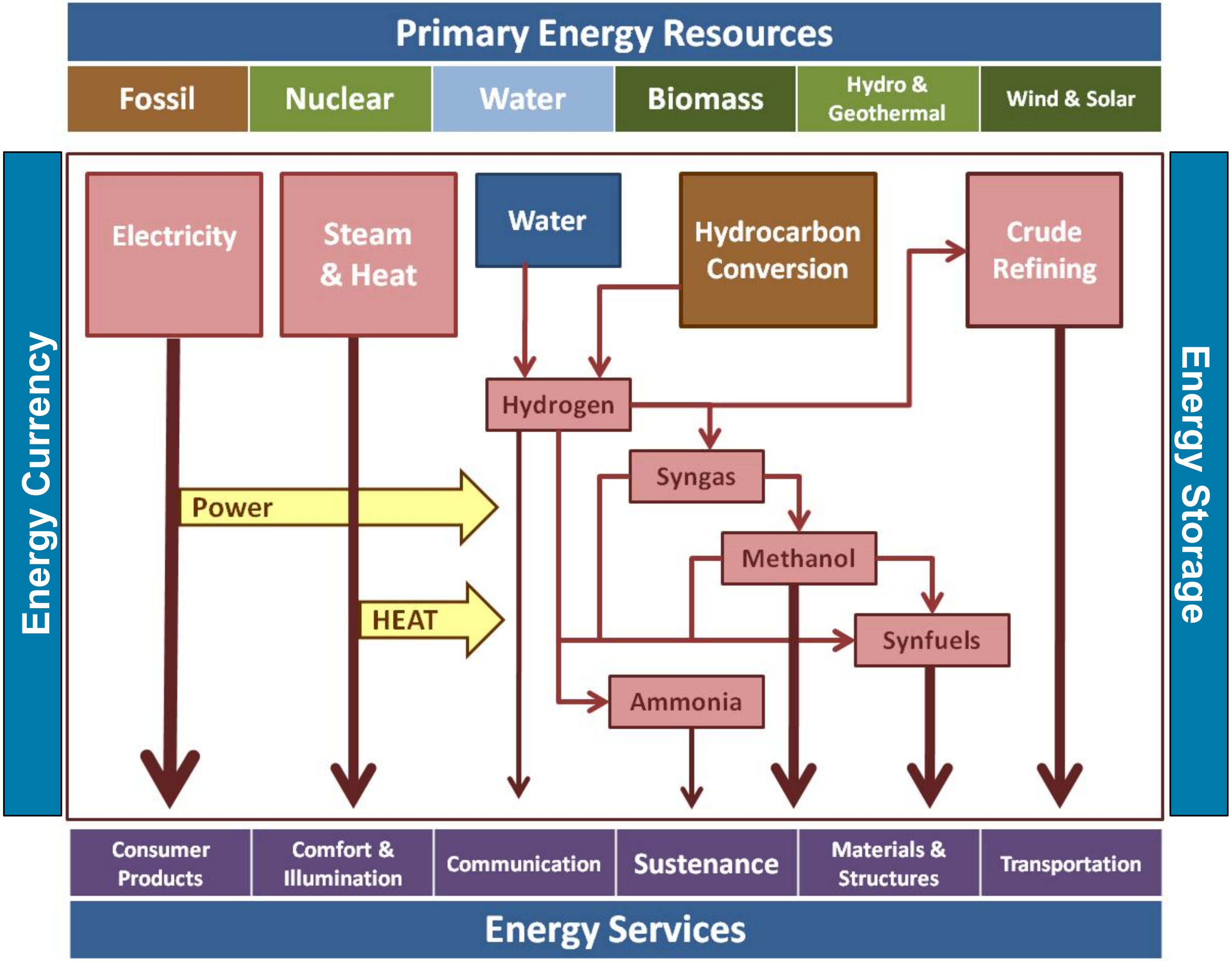
Decarbonizing the Industrial Sector is Challenging



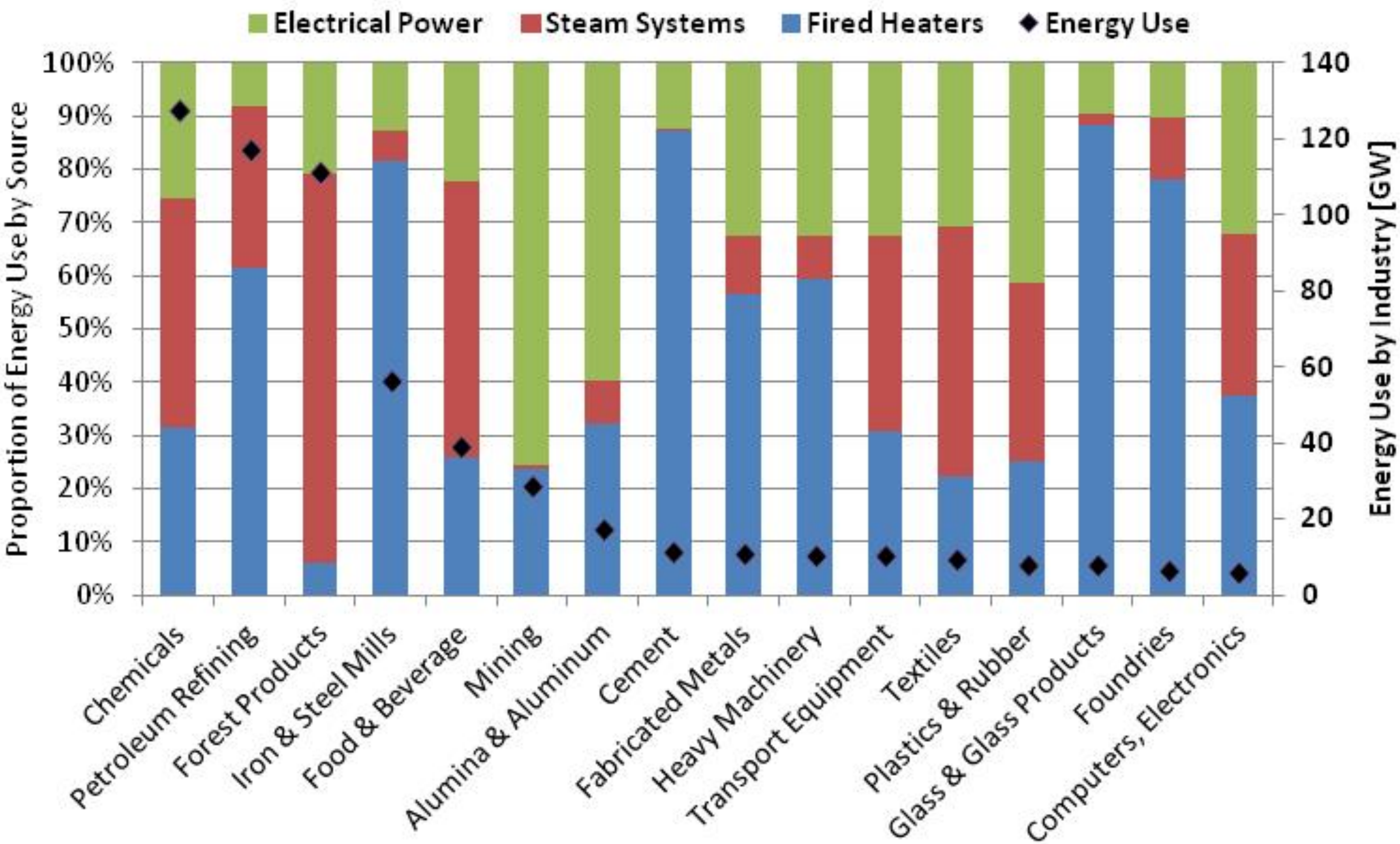
Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2015. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combustion of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

38% Electricity
34% Transportation
18% Industrial
6% Residential
4% Commercial

18% of the U.S.'s GHG emissions are direct emissions from the industrial sector. Alternative energy sources are limited due to heat delivery requirements.


Primary Energy Resources
Fossil
Nuclear
Water
Biomass
Hydro & Geothermal
Wind & Solar
Energy Currency
Electricity
Steam & Heat
Water
Hydrocarbon Conversion
Crude Refining
Hydrogen
Syngas
Power
Methanol
HEAT
Synfuels
Ammonia
Energy Storage
Consumer Products
Comfort & Illumination
Communication
Sustenance
Materials & Structures
Transportation
Energy Services

Energy use by U.S. manufacturing and mining industries for 2004



Data from Pelligrino et al., 2004, DOE IPT Report. Plotted by Ruth et al., 2014, Energy Conversion and Management.

Principal Manufacturing Industries

- Industries requiring steam heating:

	Industry Application	Conventional Energy Source or Conversion Process	Heat Source Temperature (°C)	Potential Nuclear Reactor Energy Delivery
Steam Heating	District heating Drying processes Evaporation processes	Combined heating and power with fossil fuels or biomass combustion	30 – 200	Hot water LP steam
	Miscellaneous steam applications Pulp and paper products Food processing	Fossil-fired boilers Black liquor combustion	100 – 300	IP steam
	Petrochemical refineries	Oil, natural gas, tail gas, and petcoke boilers	Distillation: 200 – 500 Thermal Cracking: 400 – 650	HP steam Hydrogen
	Hydrogen production by water splitting	Electrolysis Thermochemical looping reactions	Water Electrolysis: < 100 High T. Electrolysis: 750 – 850 Thermal Loops: 450 – 900	IP – HP steam Hot gas Molten salt

LP – low pressure steam (< 1 MPa)
IP – intermediate pressure steam (1 – 10 MPa)
HP – high pressure steam (> 10 MPa)

Principal Manufacturing Industries

- Industries requiring indirect heating:

	Industry Application	Conventional Energy Source or Conversion Process	Heat Source Temperature (°C)	Potential Nuclear Reactor Energy Delivery
Indirect Heating	Inorganic minerals production (phosphates, soda ash/sodium hydroxide, chlorine, fertilizers, etc.)	Fossil-fired heaters	Minerals retorting: 350 – 500 Minerals concentration:150 – 250	HP steam Hot gas Molten salt
	Biofuel refineries	Biomass-processing and thermal conversion Distillation Steam methane reforming	Distillation: 150 – 200 Torrefaction: 250 Pyrolysis: 500 Gasification: 850 – 1000	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for fuels upgrading
	Chemicals manufacturing (methanol, 1,4 butanediol ethylene/ propylene, acetic acid, formaldehyde, resins, hexamethylene diamine etc.)	Distillation / Concentration Heat transfer reactors Fossil-fired heaters Heat recuperation	Distillation: 150 – 200 Softening/Melting: 150 – 300 Reactions: 300 – 600	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for chemical synthesis Electro-chemical processes
	Hydrogen production from hydrocarbons	Two-stage auto-thermal partial oxidation of NG	750 – 900	Hot gas Molten salt

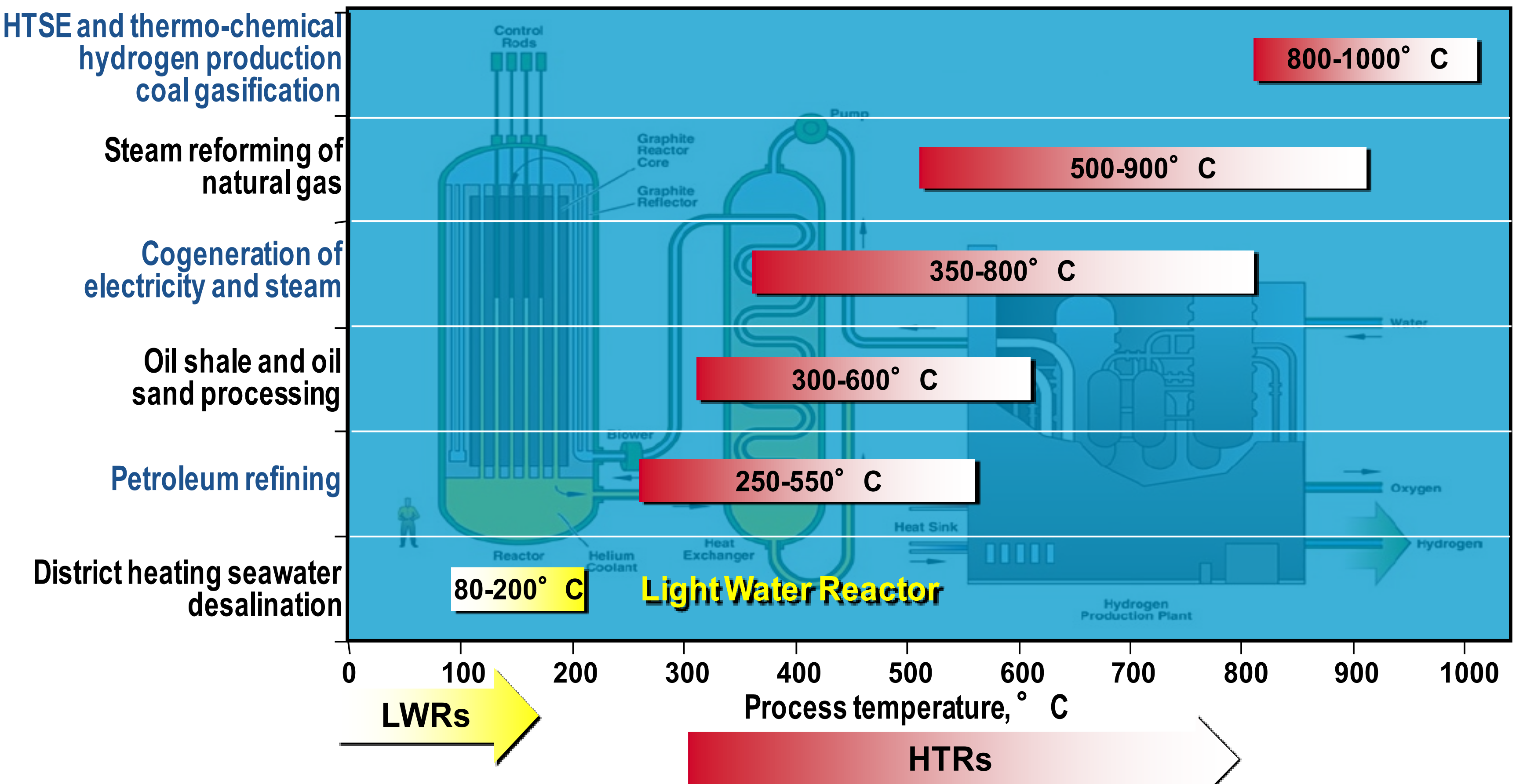
Principal Manufacturing Industries

- Industries requiring combustion and electric arc heating:

	Industry Application	Conventional Energy Source or Conversion Process	Heat Source Temperature (°C)	Potential Nuclear Reactor Energy Delivery
Combustion & Electric Arc	Coal gasification for synfuels and chemicals synthesis	Partial oxidation Shift reactor Fischer-Tropsch fuels (F-T) Methanol to gasoline (MTG)	> 1,000 – 1,300	O_2 for oxy-fired gasifier H_2 for fuels synthesis
	Glass and fused silica manufacturing; Iron and steel making; Aluminum production; etc.	Fossil-fired heaters Metallurgical coke H_2 for reduction Electricity from inexpensive supplier	> 1,000 – 1,500	Induction heating, Electric arc / Plasma Electro-chemical processes H_2 enriched flames H_2 as a reductant
	Portland cement ($xCaO- yAl_2O_3- zSiO_2$) Lime (CaO / CaOH)	Combustion-fired kiln	> 1,300 – 1,800	H_2 enriched flames H_2 as a reductant

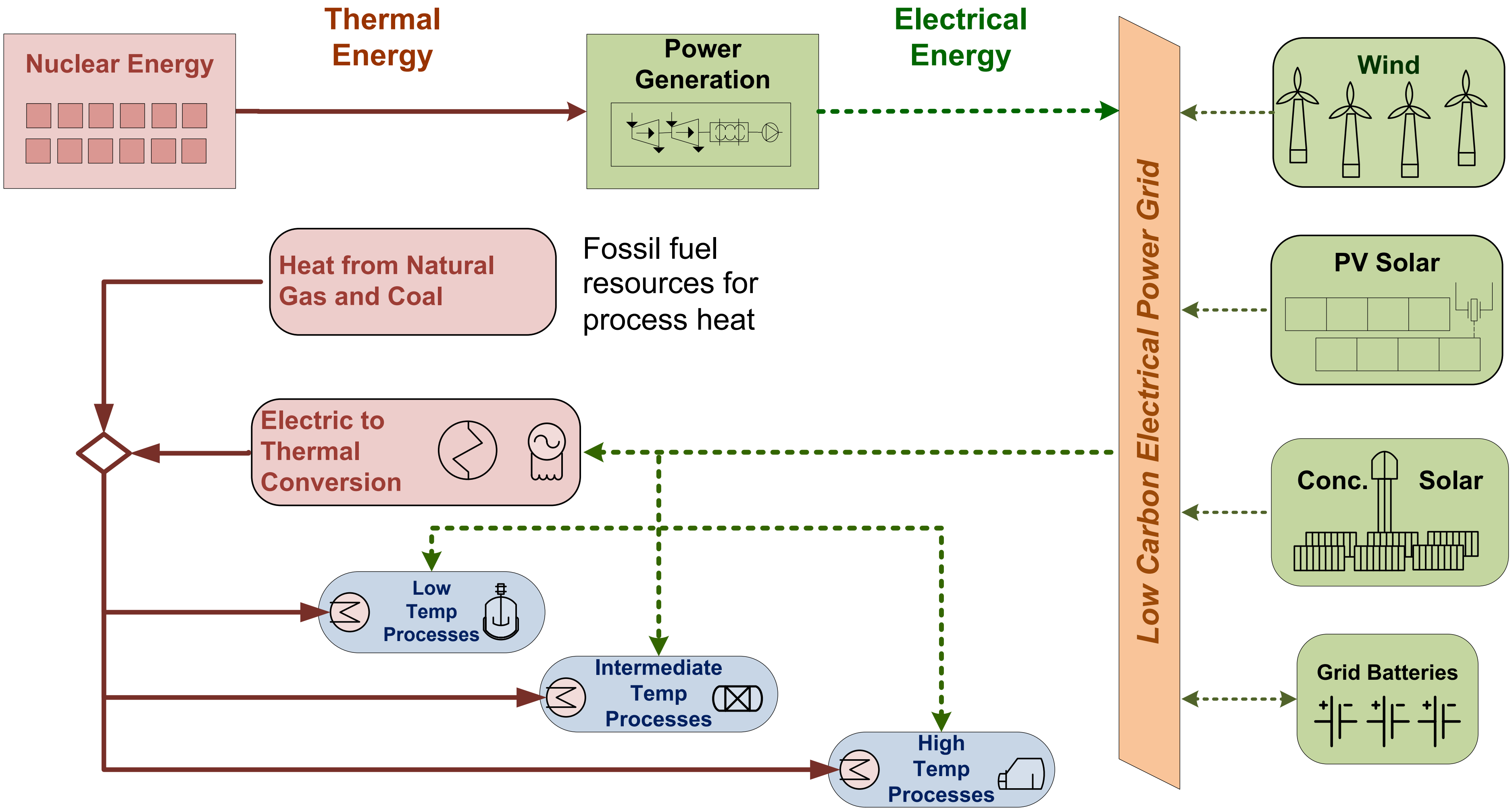
LP – low pressure steam (< 1 MPa)
IP – intermediate pressure steam (1 – 10 MPa)
HP – high pressure steam (> 10 MPa)

Nuclear Applications Beyond Electricity

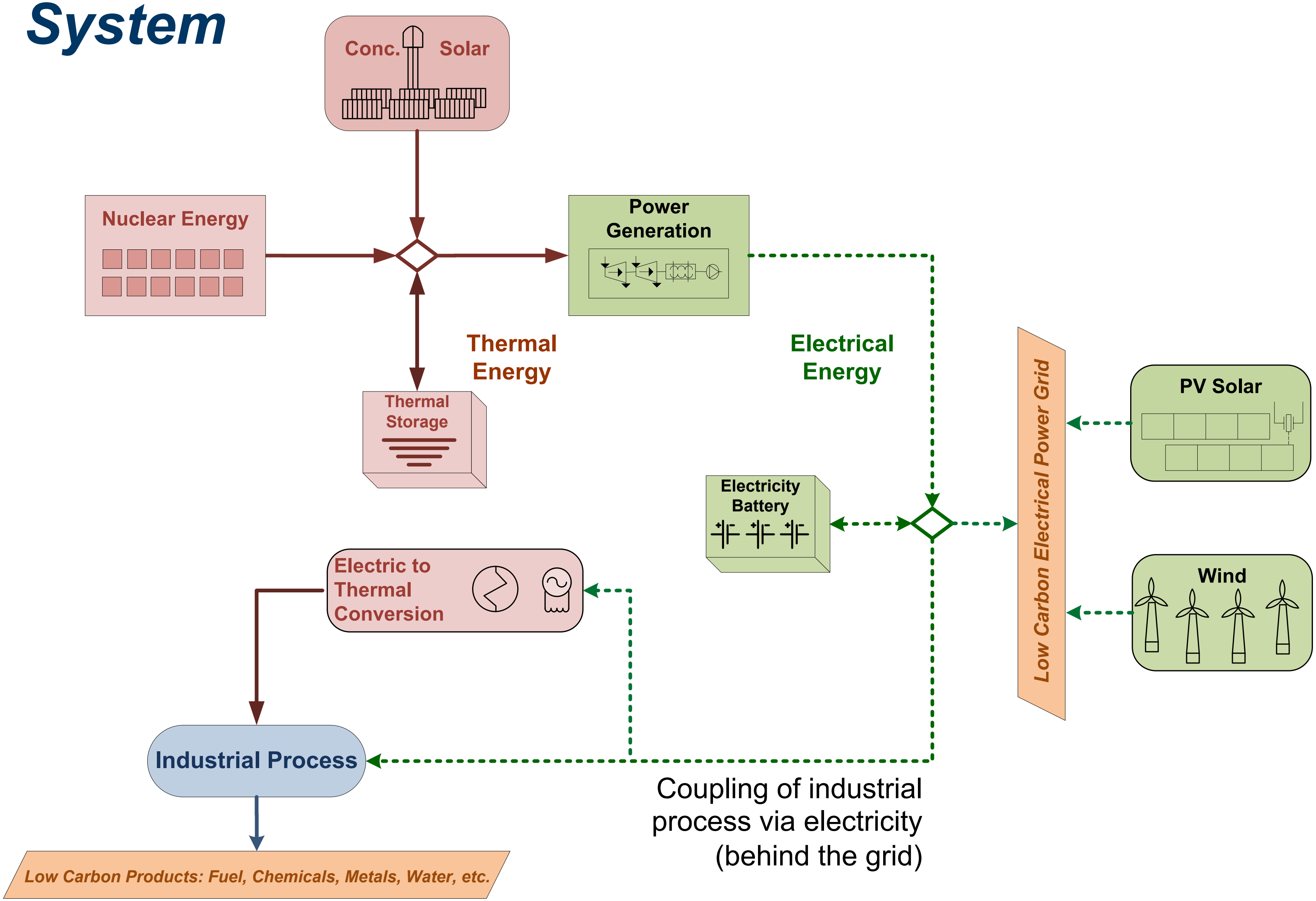


**Lower temperature reactors can support these applications via heat recuperation and topping.

Base Case: Current State of the Grid

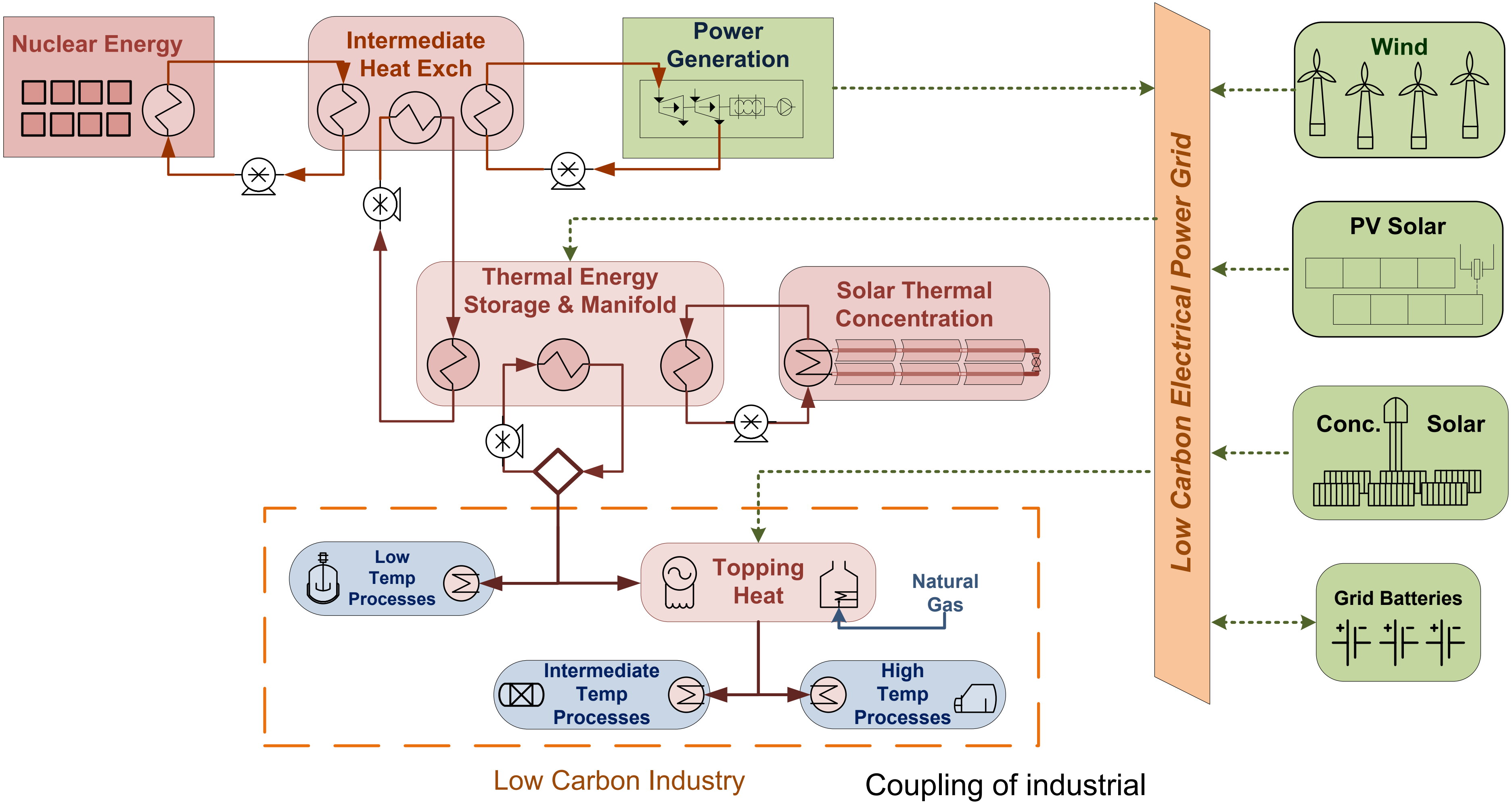


Loosely Coupled, Electricity Only Hybrid Energy System



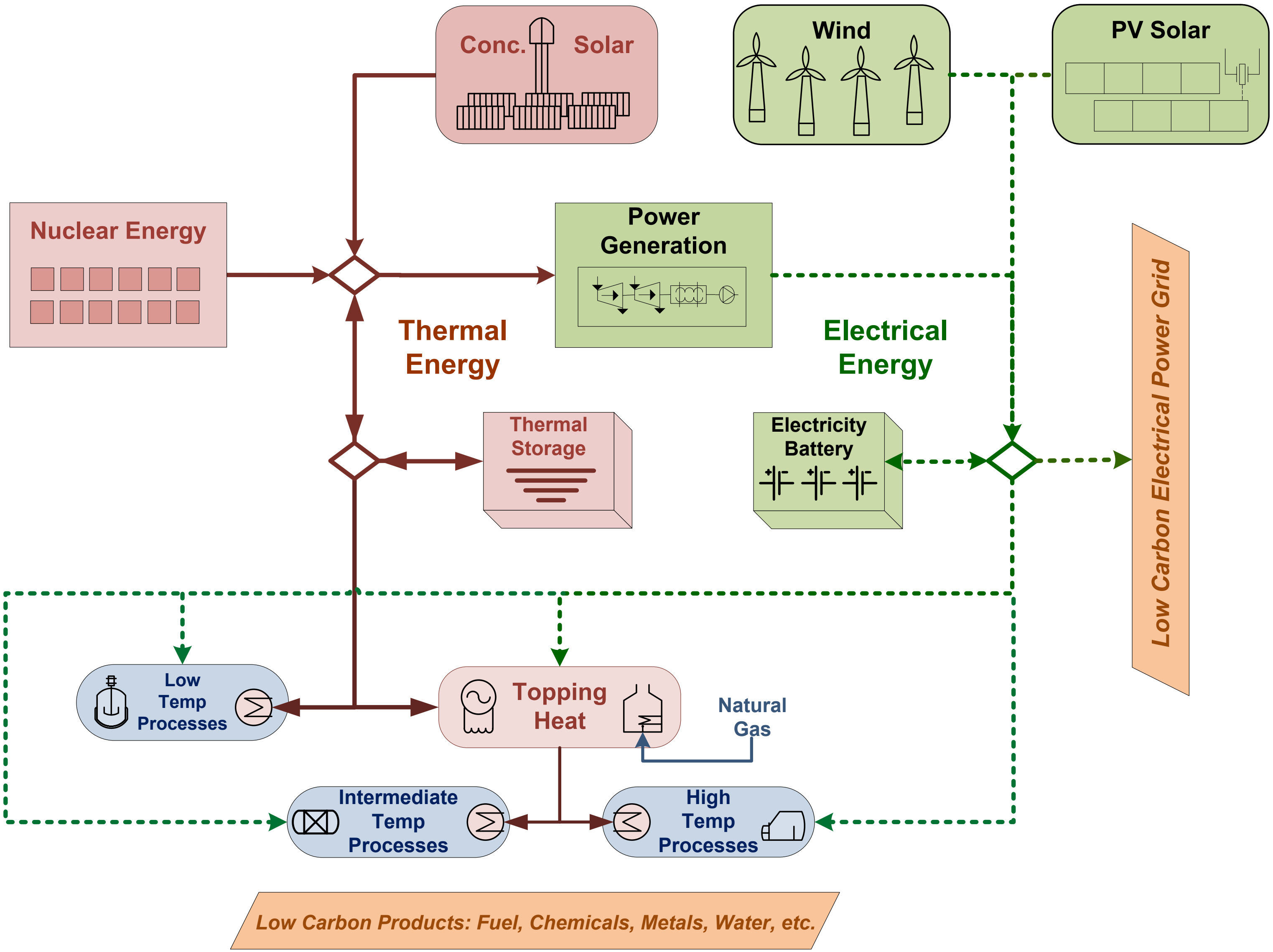
Coupling of industrial process via electricity (behind the grid)

Thermally Coupled Hybrid Energy System (HES)



Coupling of industrial process via heat and electricity

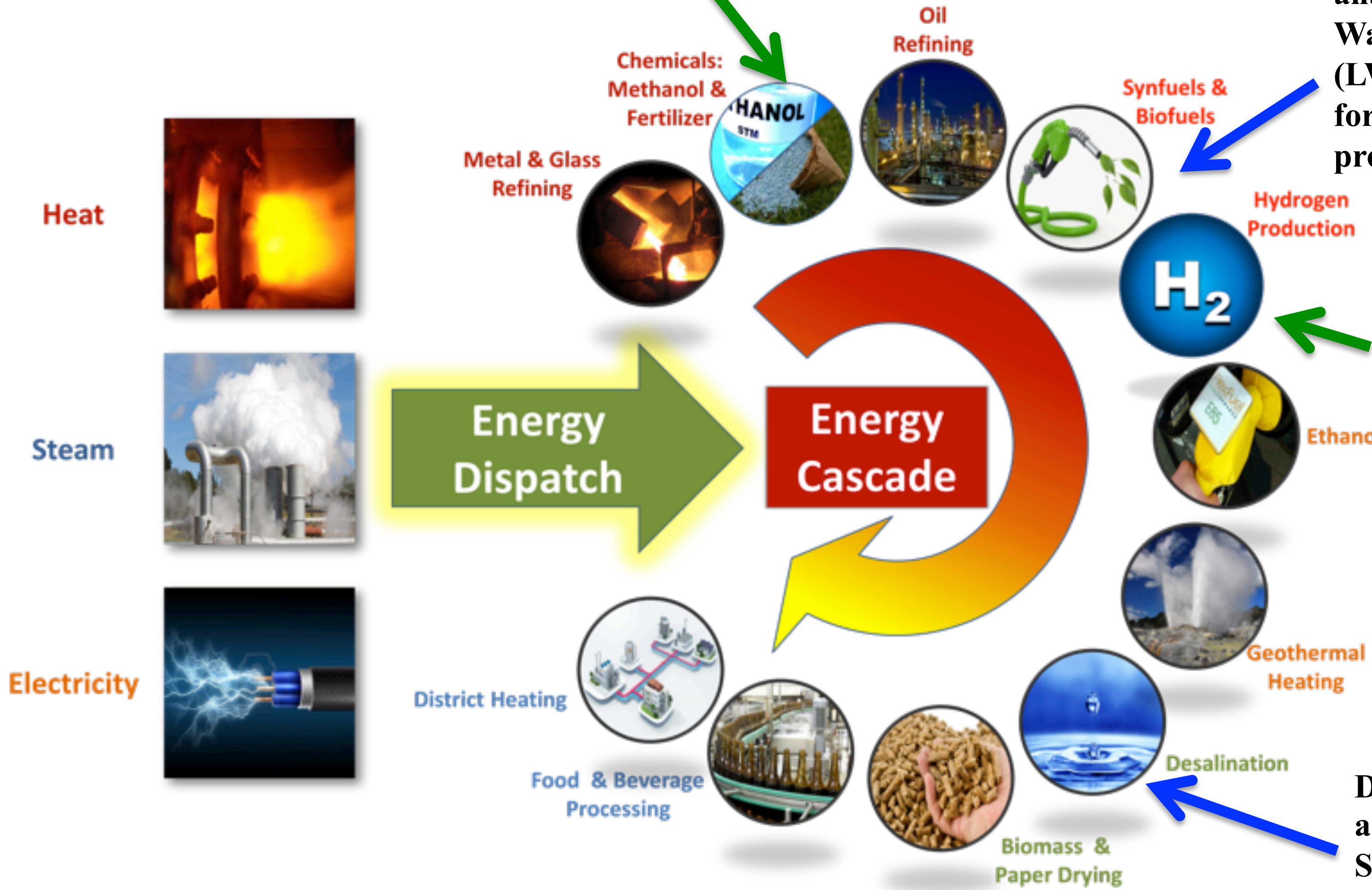
Tightly Coupled Hybrid Energy System



Industrial Process Opportunities for HESs

Methanol co-generation analysis, high temperature reactors (HTRs).

Dynamic HES analysis, Light Water Reactor (LWR) + Wind for synfuel production.

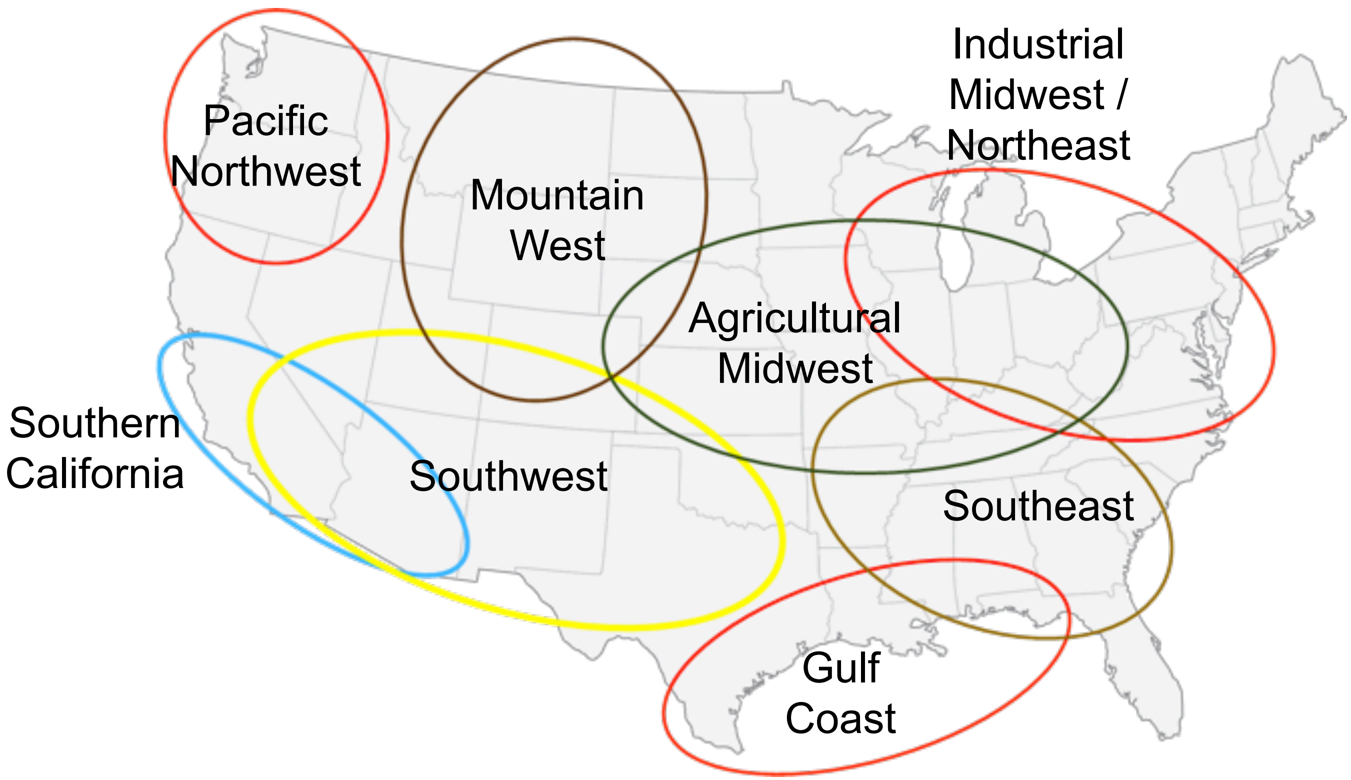


Dynamic H_2 generation with steam electrolysis.

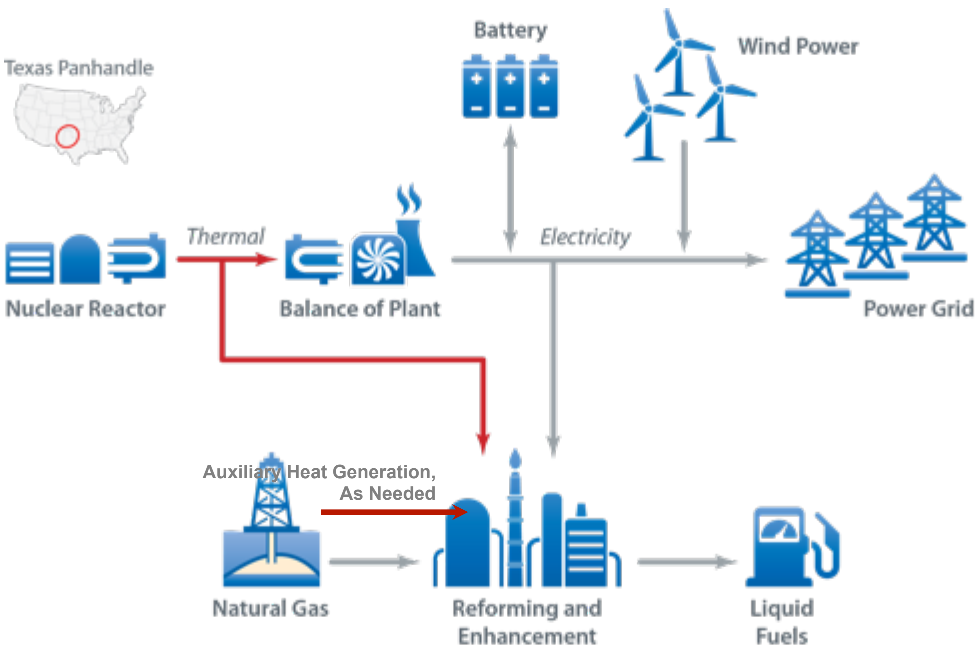
Dynamic HES analysis, LWR + Solar PV for desalination.

Finding measureable benefits:
Identification of High Priority Regional Cases

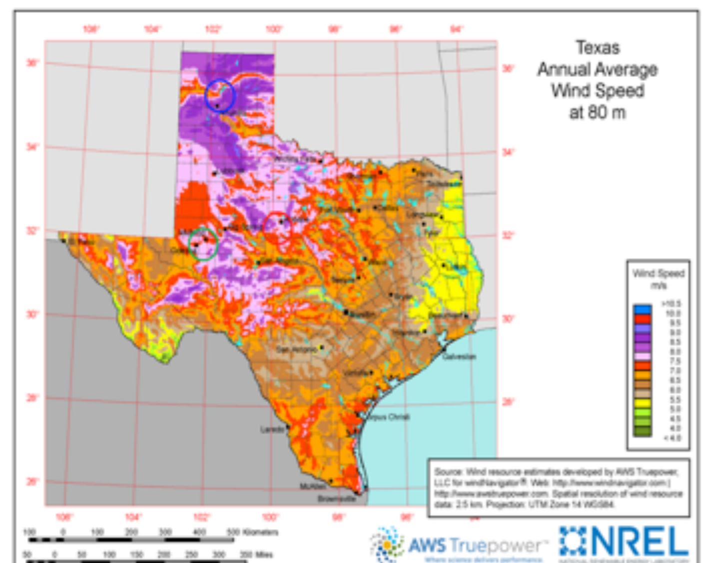
- Identification of potential configurations in a region depends on **resources, traditional industrial processes, energy delivery infrastructure, and markets**



Initial Case 1: Texas Panhandle, Synthetic Gasoline



- Proximity of **natural gas** wells can provide the needed carbon source for liquid fuel
- **Wind** speeds sufficient to use existing or to build additional wind farms
- Electricity sold to the Southwest Power Pool of Eastern Interconnection vs. ERCOT
- 600 MWth / 180 MWe **LWR** + 45 MWe **wind**
- Diverts up to **150 MWt** to chemical plant complex
- **500 million gal** gasoline annual production



Additional options / considerations:

- Coal-to-synfuels industrial process
- Hydrogen production as an interface; provides chemical feedstock to upgrade fossil fuels

H. Garcia et al., INL/EXT-15-34503, M3AT-15IN2601016 (2015)

Initial Case 2: Arizona, Brackish Water Desalination

- 180 MWe **LWR** Power (i.e., small-modular reactor)
- Up to **30 MWe solar** PV
- System up to **45 MWe reverse osmosis** plant, producing **22,000 to 56,000 m³/hr of water** for 950,000 to 2.85 million people

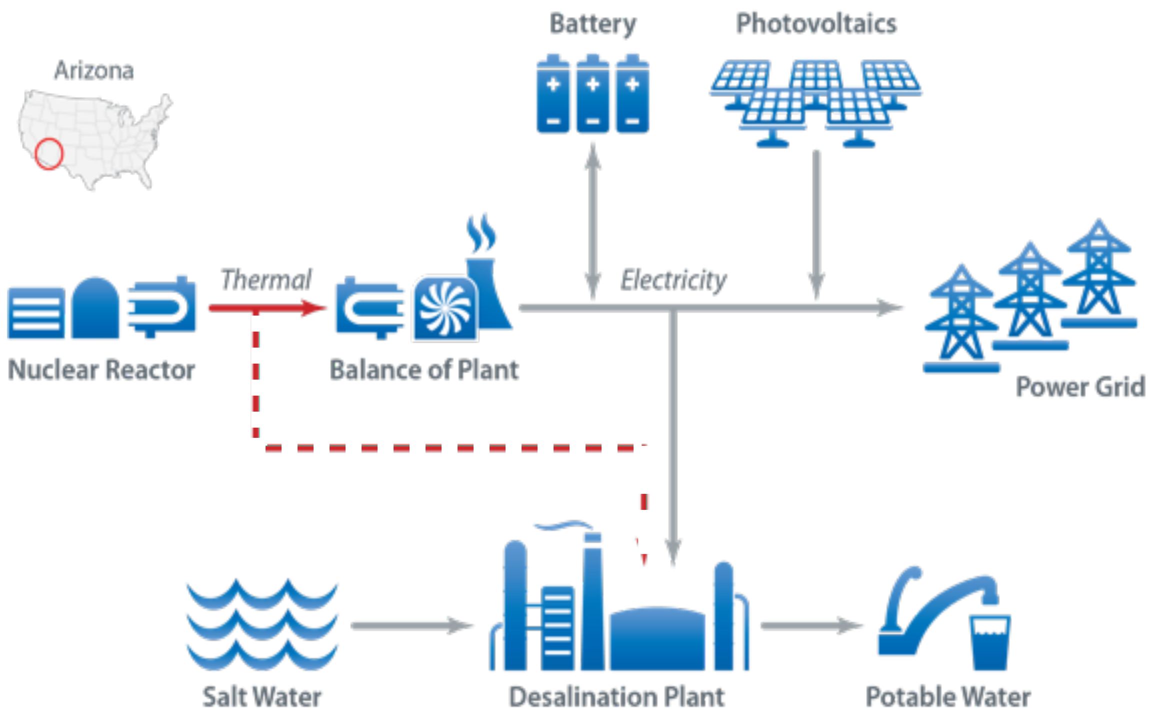


FIGURE 1. BRACKISH GROUNDWATER AREAS IN ARIZONA

Additional options / considerations:

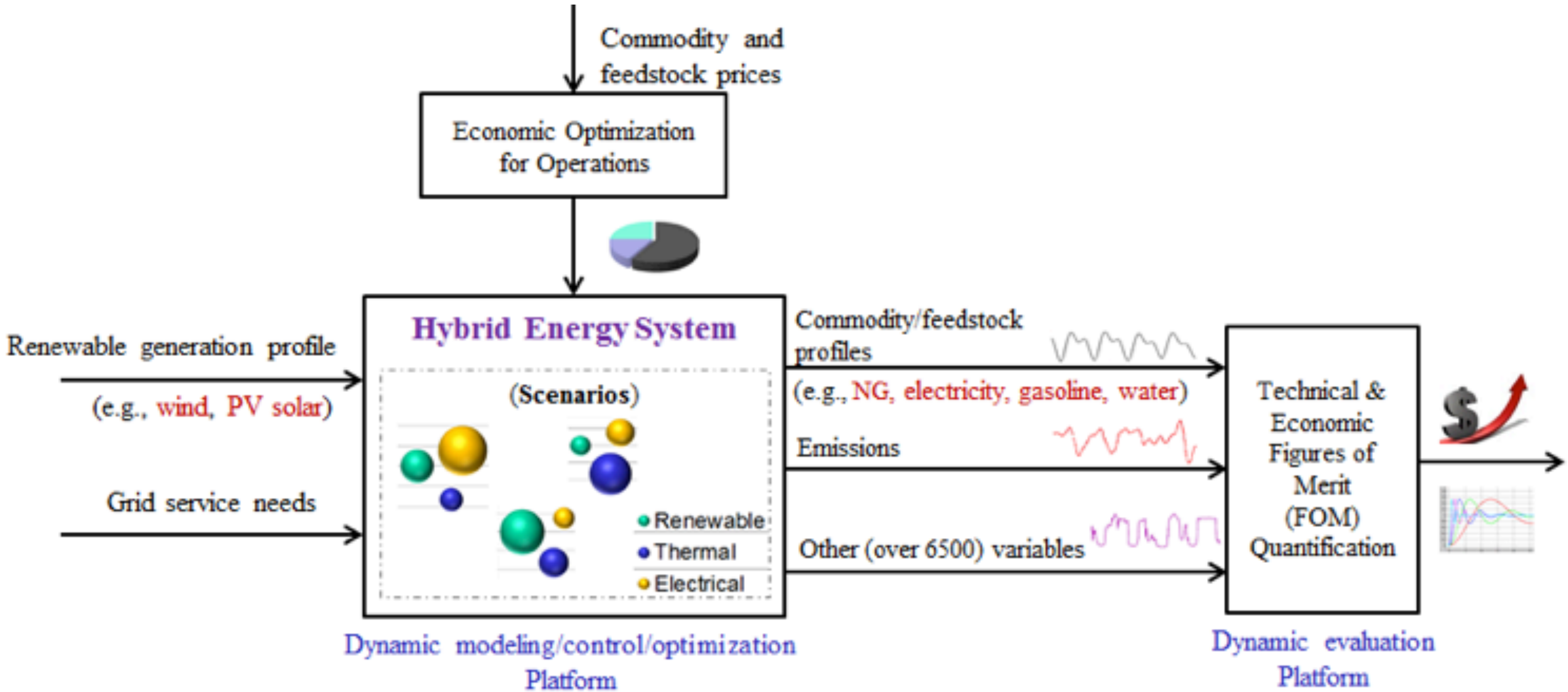
- Concentrated Solar
- Land-based wind

H. Garcia et al., INL/EXT-15-34503, M3AT-15IN2601016 (2015)

Dynamic Analysis: Evaluation Parameters

- Technical Figures of Merit
  - Electric power frequency stability
  - Maximum renewable penetration
  - Maximum renewable variability that can be accommodated
  - Minimum storage requirement
  - Response time and ramp-rate
  - Load following response
  - Operating reserve capacity
  - Minimum turndown of integrated systems
  - Startup/shutdown time
- Economic Figures of Merit
  - Pre-tax Gross Profit (PGP)
  - Net Present Value (NPV)
  - Payback time
  - Internal Rate of Return (IRR)
- Future Evaluation:
  - Minimum greenhouse gas emissions
  - Resiliency
  - Security of national energy supply

Dynamic Analysis Information Flow



Preliminary Results (1-yr analysis period, fixed subsystem sizes)

- **Texas Panhandle:**
  LWR + Wind → Elect. + Gasoline
- 45 MW_e available for operating reserve services, per case assumptions – needs further study
- IRR 14.5%, 8 yr payback period
- Demonstrated renewable penetration >20% of total system generation
- Ramp rate 0.3 MW_e/s demonstrated
- $1.4x10^6$ metric ton reduction in CO_2 emissions through use of nuclear baseload vs. natural gas-fired baseload unit

- **Northeast Arizona:**
  LWR + PV → Elect. + Water (RO)
- 30 MW_e available for operating reserve services, per case assumptions – needs further study
- IRR 8.2%, 16 yr payback period
- Demonstrated renewable penetration >14% of total system generation
- Ramp rate 2.1 MW_e/s demonstrated
- $1.4x10^6$ metric ton reduction in CO_2 emissions through use of nuclear baseload vs. natural gas-fired baseload unit

Key Take-aways:

•Industrial integration provides additional revenue streams for nuclear and renewables; increases revenue over electricity-only applications

•At times, the HES bids into the contingency reserve market – reduce electricity available to the grid and reduce price suppression at times of high wind or solar output

•Reduce industrial carbon emissions from the industrial sector by providing low-carbon heat to industrial applications

Challenges to Address

- **Integration Value:** Increased value of system components to both the owner of the hybrid system and to the grid as a whole; added risk of integration relative to improvement in efficiency and energy availability.
- **Technical:** Novel subsystem interfaces; ramping performance; advanced instrumentation and control for reliable system operation; integrated system safety; commercial readiness.
- **Financial:** Business model; cost and arrangement of financing and risk/profit taking agreements; risks of market and policy evolution; capacity factors (capital utilization).
- **Regulatory:** Projected environmental regulations; deregulated/ regulated energy markets; licensing of a co-located, integrated system; involvement of various regulatory bodies for each subsystem and possible “interface” issues.
- **Timeframe:** Resolution of issues/challenges within the timeframe established based on external motivators (e.g. EPA recommendations).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